Determining atmospheric electric fields through radio emission from air showers

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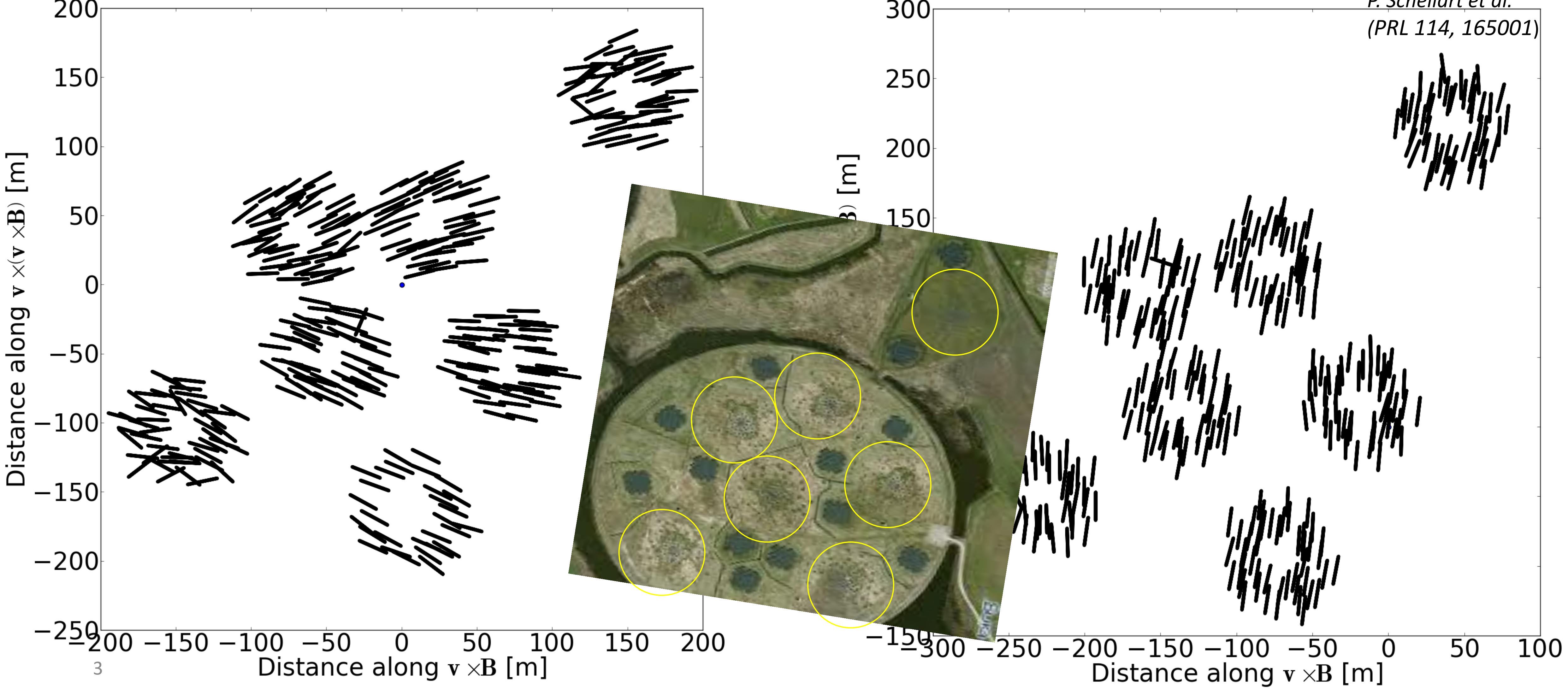
Outline

- Atmospheric electric fields affect radio footprint ←→
  determine atmospheric fields from the footprint
  - Mechanism; distinguish $\vec{E}_{//}$ and $\vec{E}_{\perp}$
- Procedure we use to determine the structure
  - Stokes parameters (Intensity & Linear and circular polarization)
  - Fit the complete footprint
- Results – strong fields in non-thunderstorms
- Results - tomography

Observations; polarization footprint

Fair weather vs thunderstorm (same angle)

P. Schellart et al. (PRL 114, 165001)

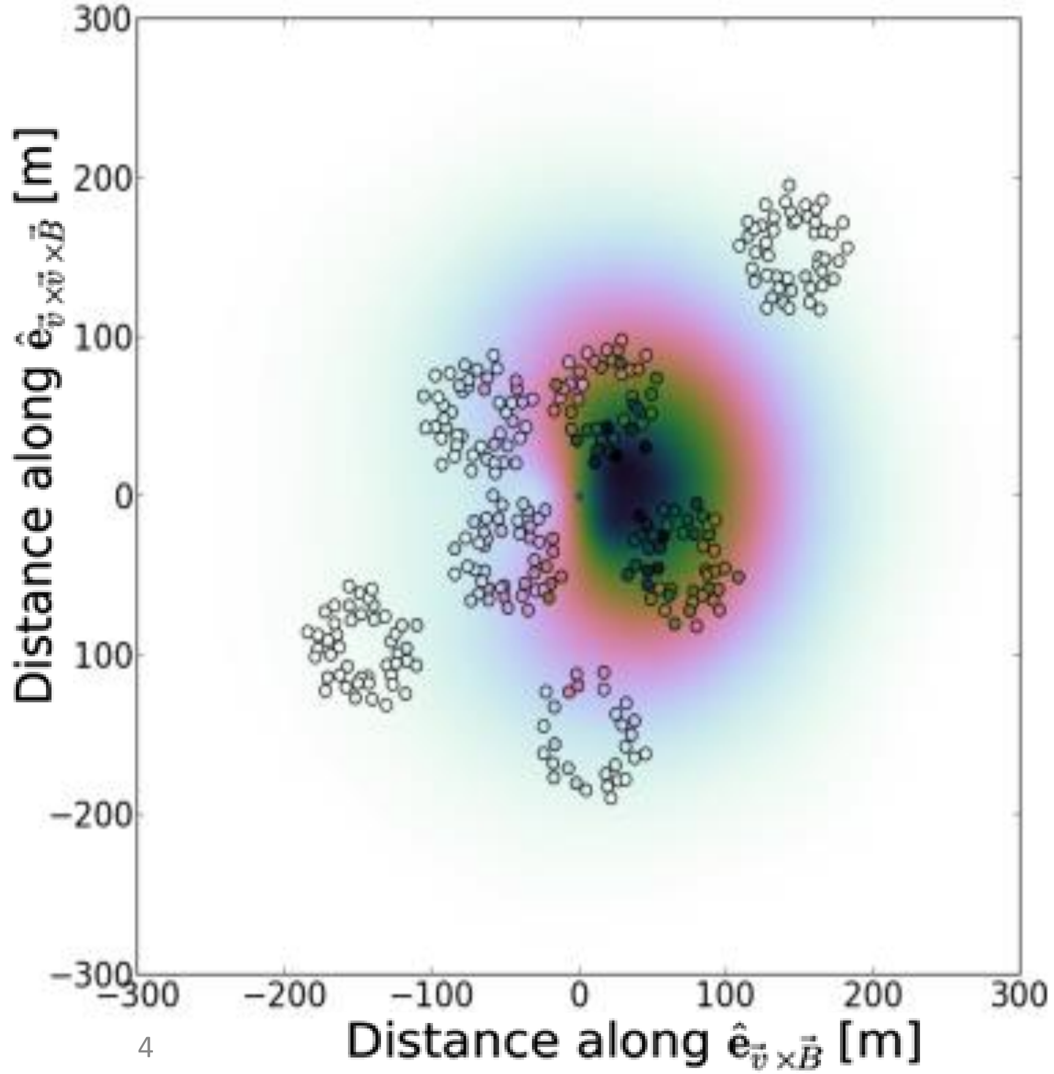


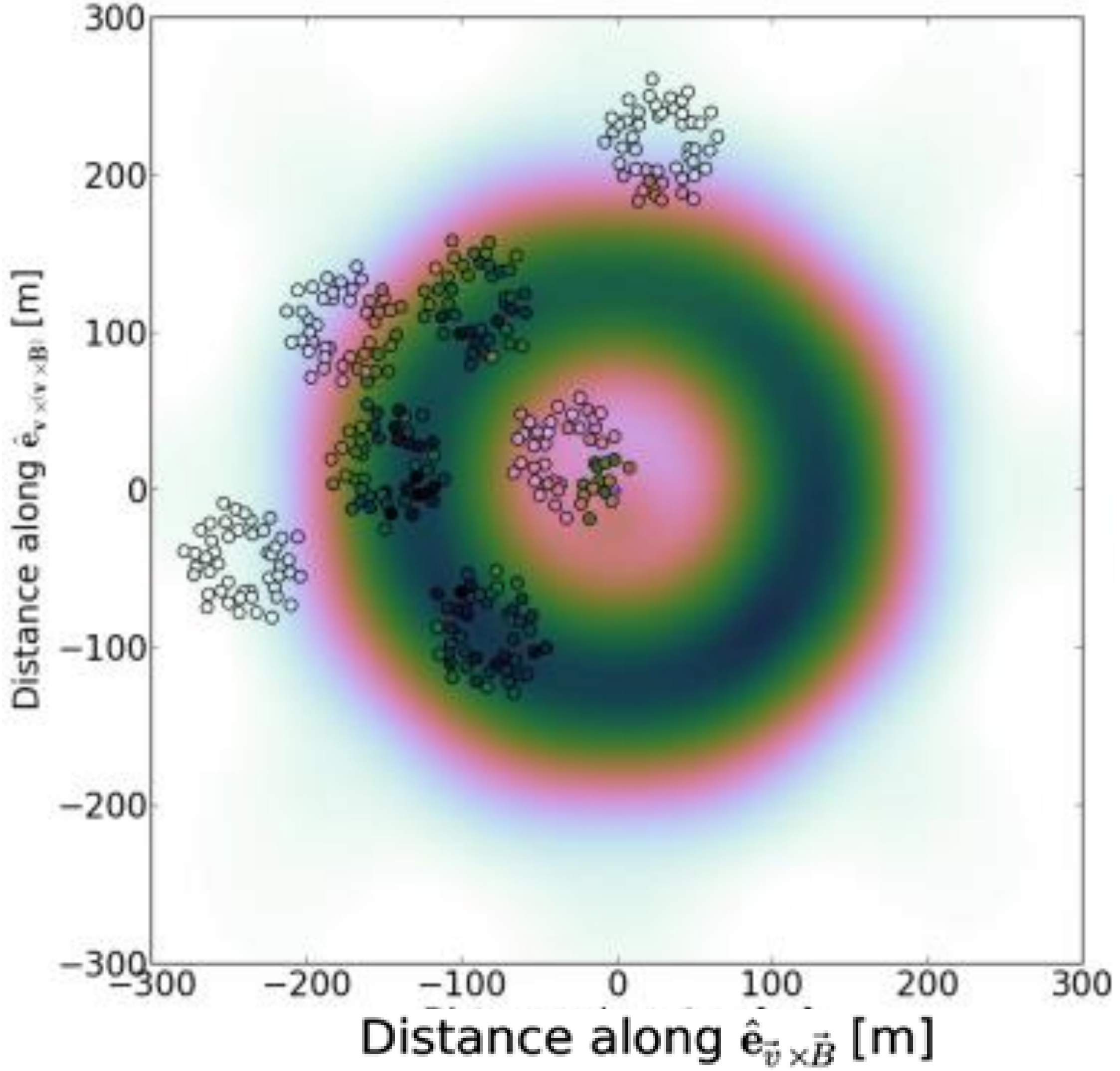
Observations; intensity footprint

S. Buitink et al.
PRD 90, 082003 (2014)

Fair weather vs thunderstorm

P. Schellart et al.,
PRL 114, 165001 (2015)





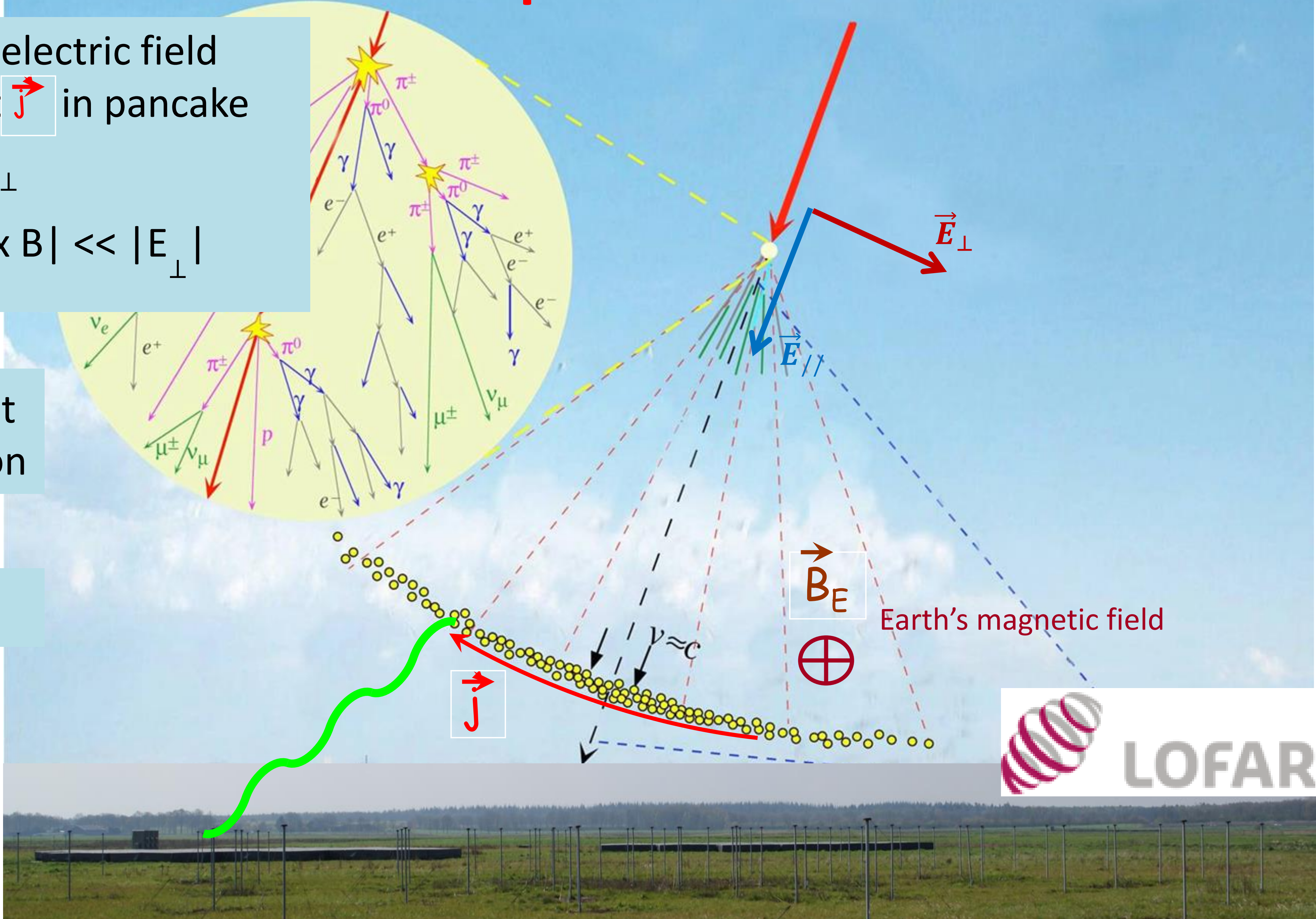
Radio emission in presence of an electric field

Earth magnetic field + electric field
induce electric current $\vec{j}$ in pancake
direction: $F = v \times B + E_\perp$

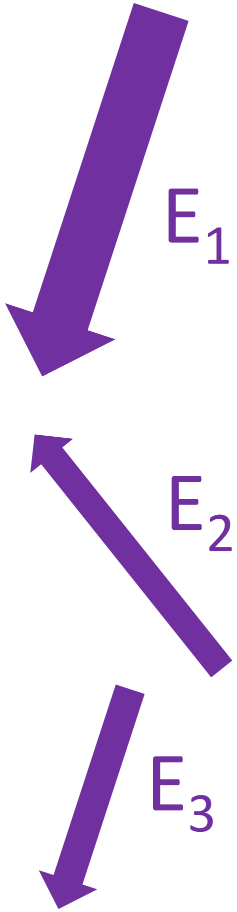
In thunderstorms: $|v \times B| \ll |E_\perp|$

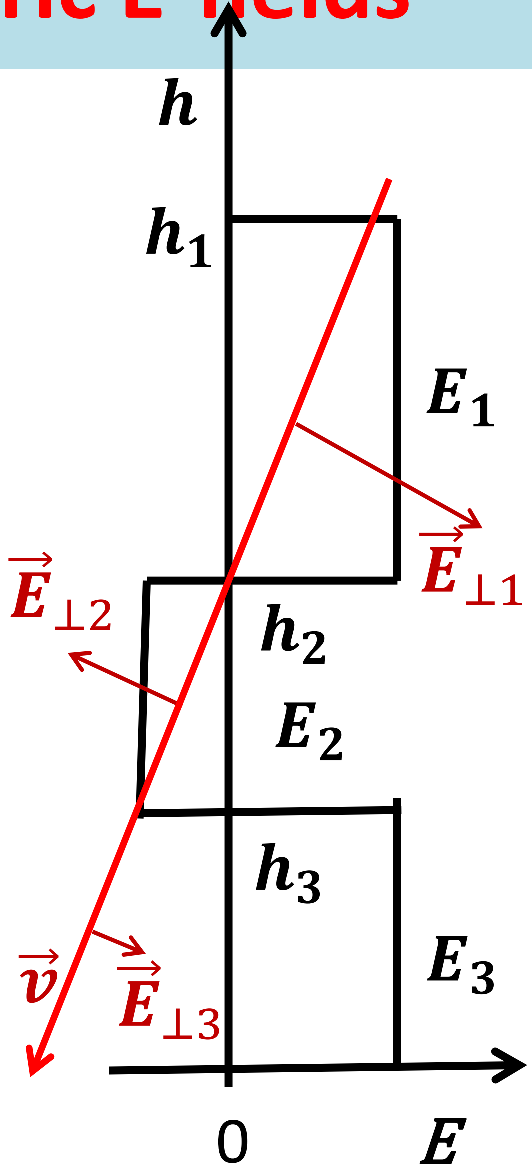
$\vec{E}_\perp$: - increases current
- changes direction

$\vec{E}_{//}$: - minor effect



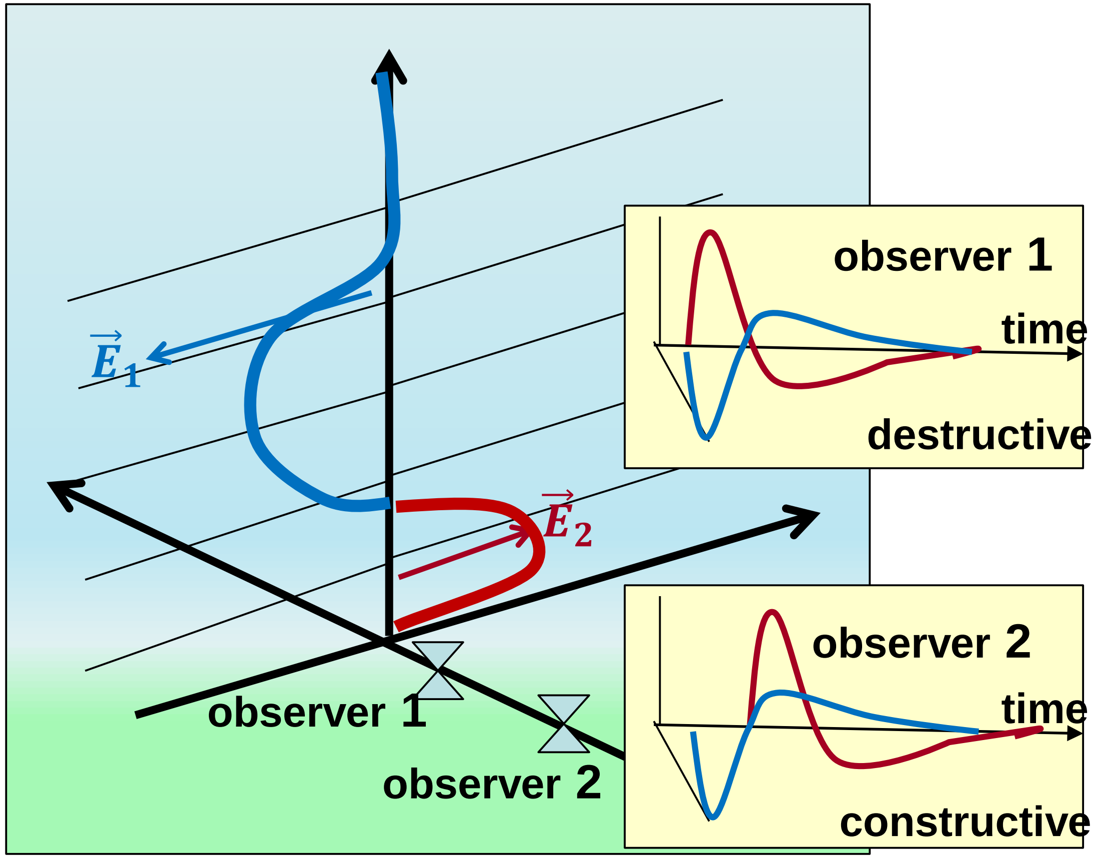
Modelling structure atmospheric E-fields





Interference of emission from different heights (a)

→ ring-like structure in intensity   if currents are opposite

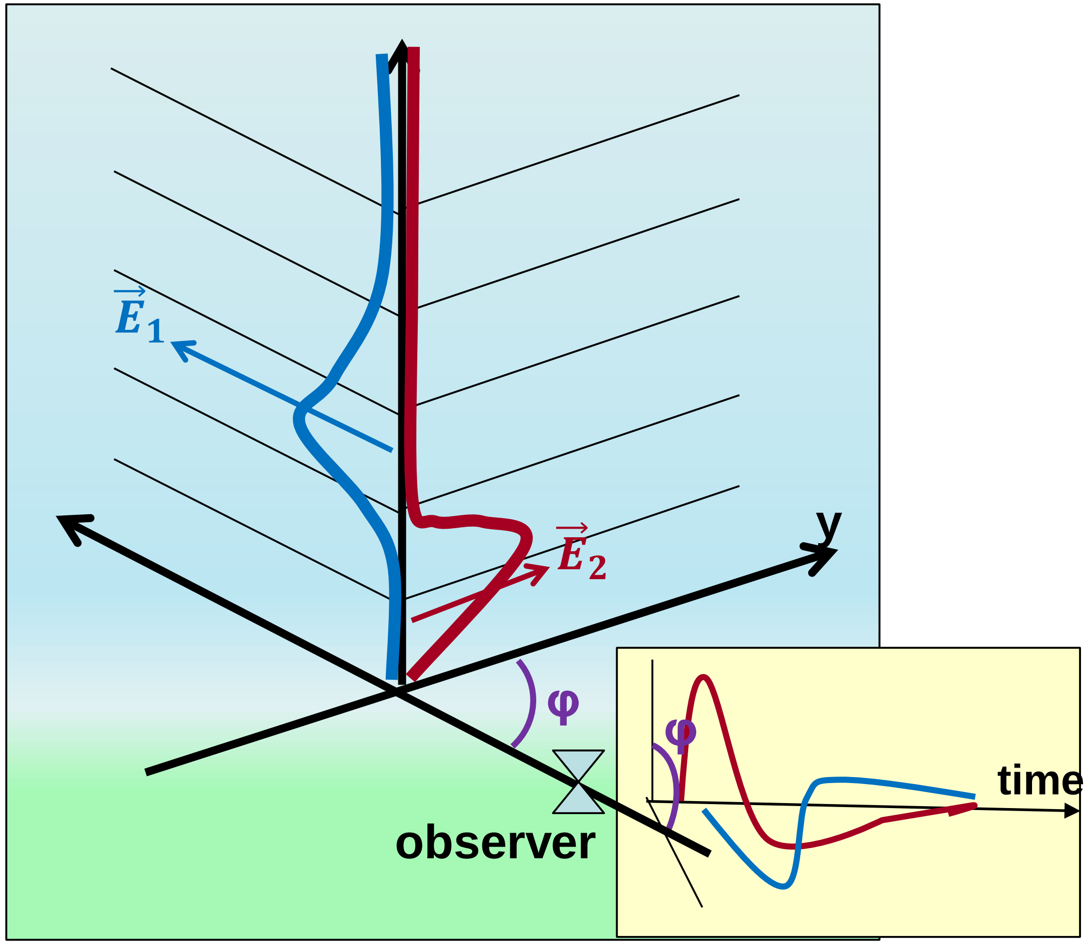


Destructive interference depends on relative arrival times, or distance to shower axis.

Signal is linearly polarized along direction of atmospheric electric field

Interference of emission from different heights (b)

→ Circular polarization if electric fields are at an angle

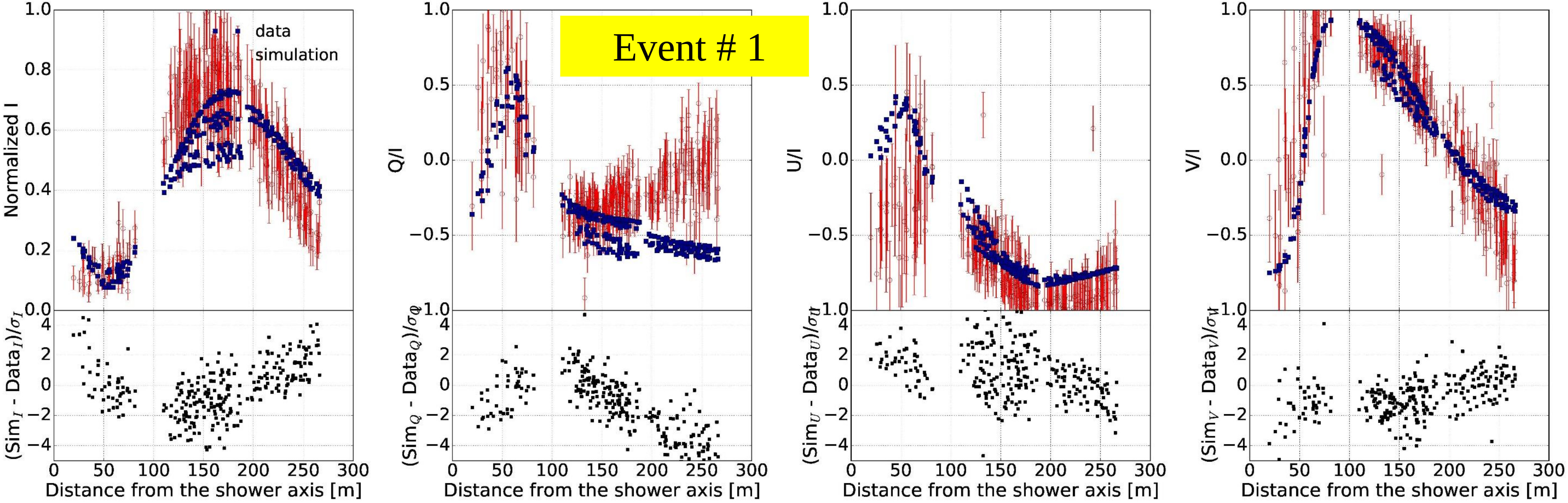


The pulses from the upper layer arrive with a delay with respect to the pulses from the lower layer resulting in a change of the polarization angle over the duration of the pulse, seen as circular polarization.

Measured signal has strong circular polarization (Stokes V/I ≠ 0)

See: Trinh et. al. (2016) *Physical Rev. D* 95, 083004

11 'Thunderstorm' events analyzed



Stokes parameters: I, Q, U, V

Linear polarization angle: 2 ϕ =atan(U/Q)

Circular polarization = V/I

Chi-square fitting of I, Q/I, U/I, V/I using MGMR3D [PRD97(2017)023005]

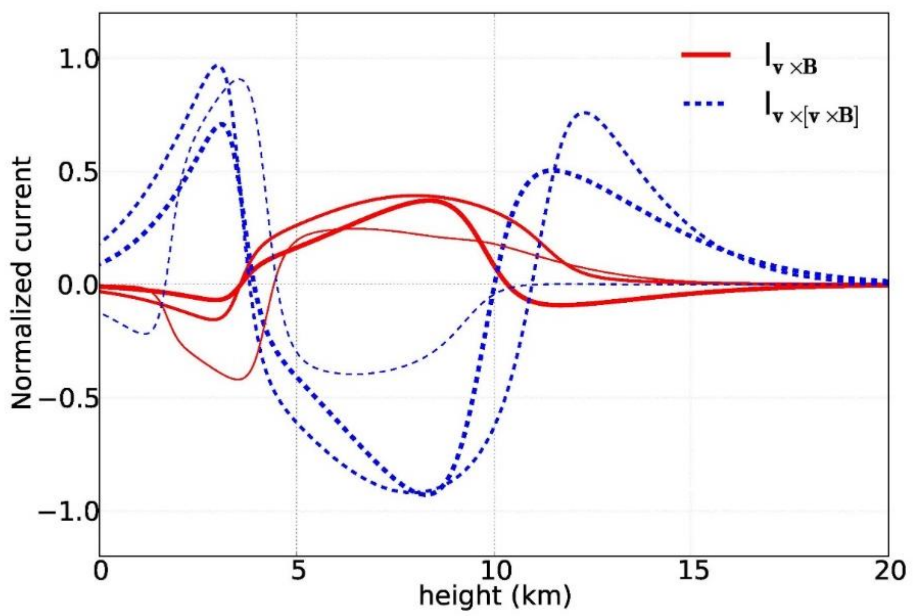
Fit: 3-layer structure of E-field & X_{max}

Final calculation with Coreas

Results for event #1

Calculation	I			II			**III**		
Energy (eV)	1.4×10^{17}			4.6×10^{16}			$\mathbf{4.0 \times 10^{16}}$		
Layer	1	2	3	1	2	3	**1**	**2**	**3**
h (km)	13.3	7.9	2.8	16.7	9.3	2.8	**7.6**	**3.3**	**1.6**
E (kV/m)	14	14	103	41	17	104	**15**	**107**	**42**
α (°)	156	-125	101	104	-109	104	**-103**	**119**	**-109**
$X_{\max}$ (g/cm^2)	526			634			**743**		
$X_{\max}$ (km)	7.3			5.9			**4.7**		
χ^2_{3D}	3.02			3.36			**3.36**		
χ^2_{C}	4.41			4.14			**3.15**		
f_r	8.2			13.3			**8.4**		

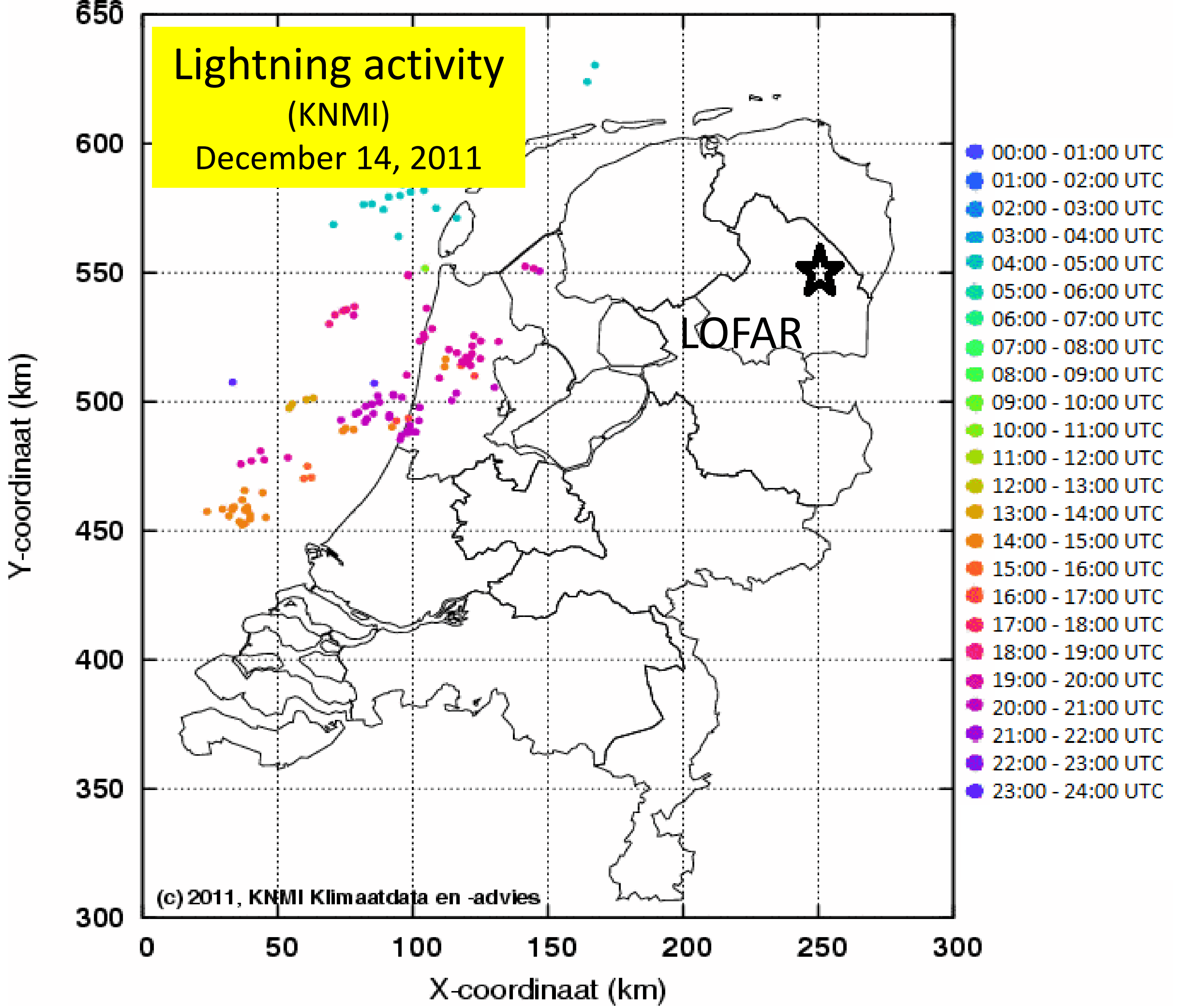
Fit results are stable



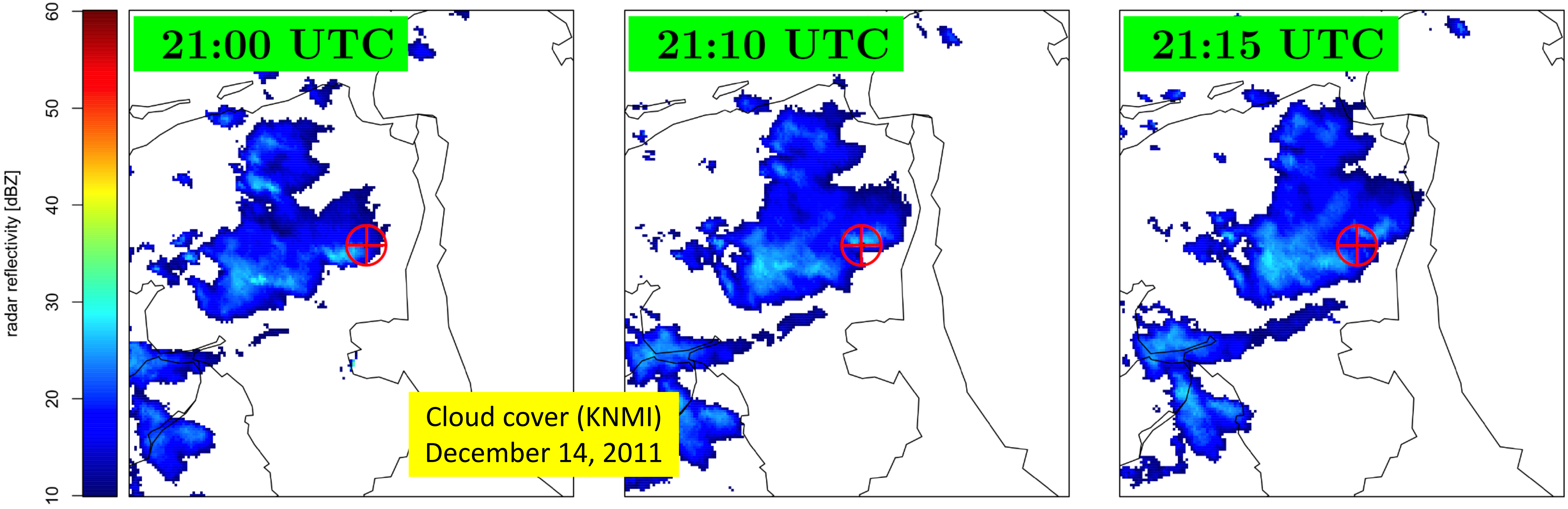
Select ideal solution based on

chi-square from CoREAS

normalization factor for radio intensity (compared to fair weather results)

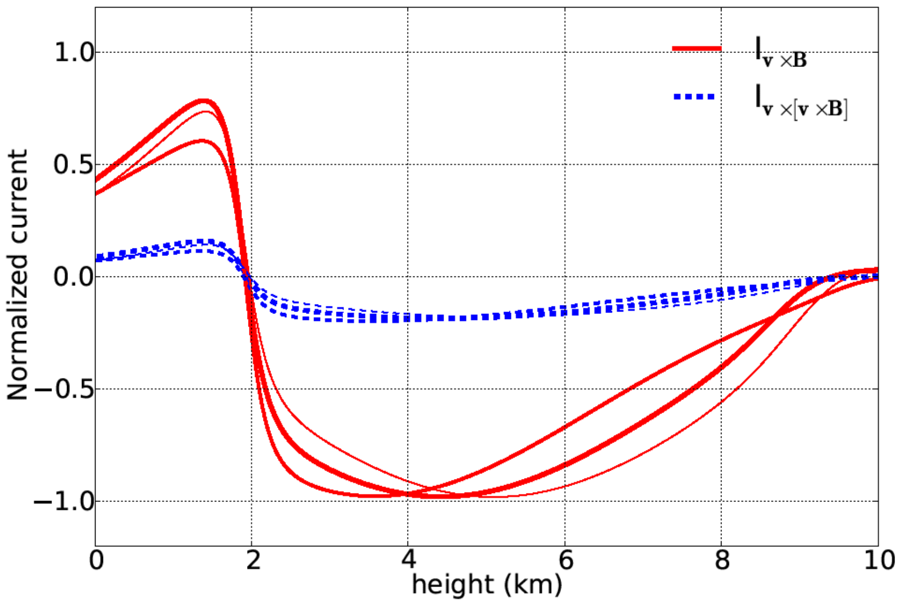


Events 1, 2, and 3 detected within 15 minutes:
UTC 21:02, 21:10, 21:15

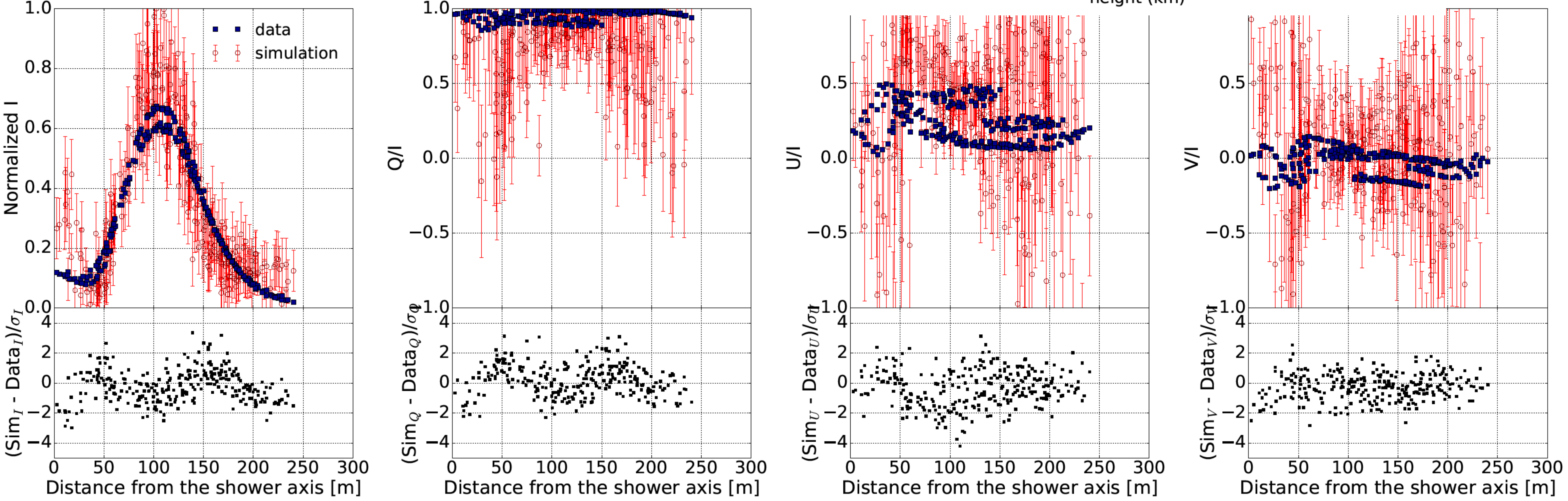


Event #1, December 14, 2011 @ 21:02:27 UTC, (θ,ϕ)= 39.4 144.8
Event #2, December 14, 2011 @ 21:10:01 UTC, (θ,ϕ)= 14.1 134.0
Event #3, December 14, 2011 @ 21:14:34 UTC, (θ,ϕ)= 24.4 333.0

Event # 2

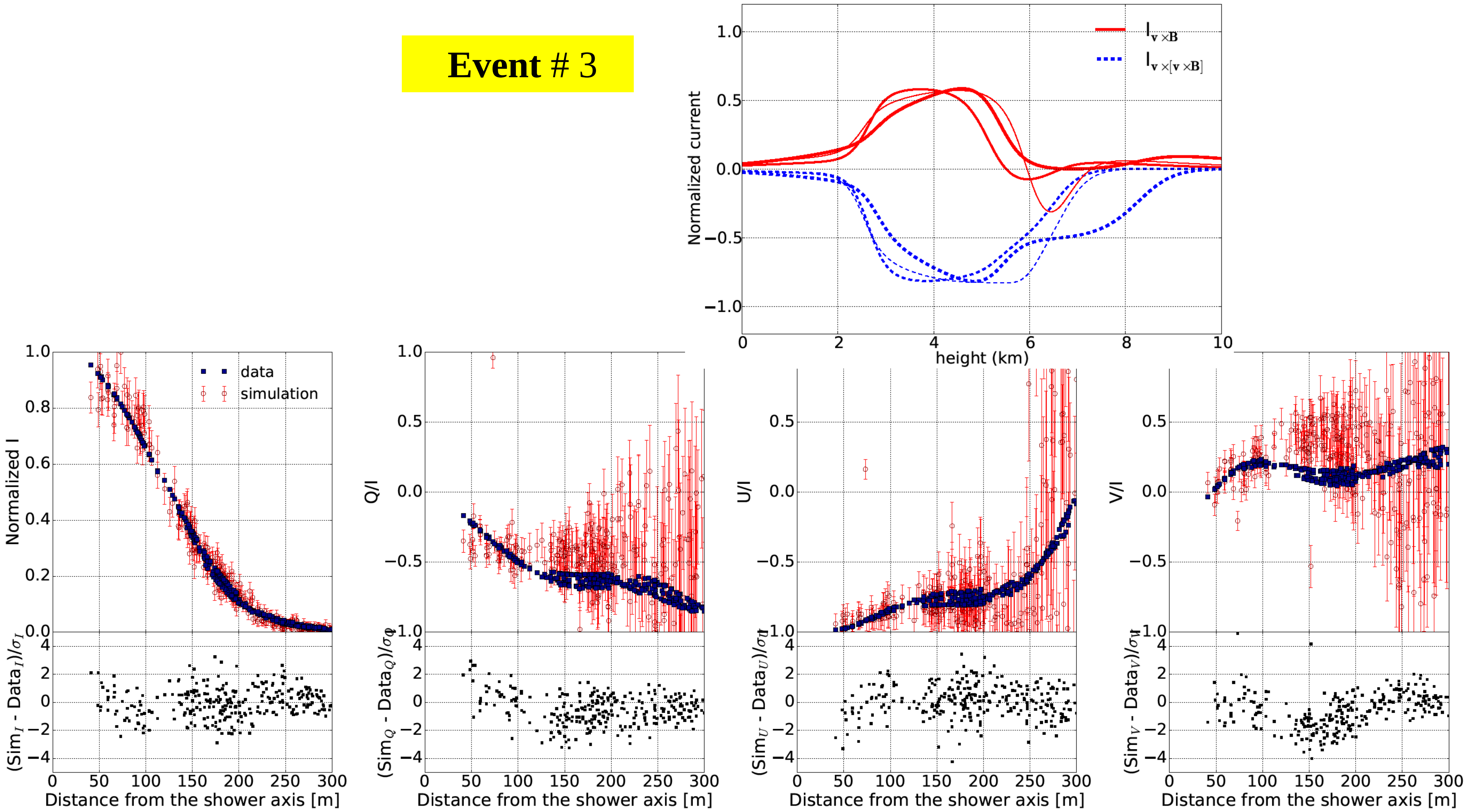


$I_{\mathbf{v}\times\mathbf{B}}$
$I_{\mathbf{v}\times[\mathbf{v}\times\mathbf{B}]}$
Normalized current
height (km)



data
simulation
Normalized I
Q/I
U/I
V/I
$(\mathrm{Sim}_I - \mathrm{Data}_I)/\sigma_I$
$(\mathrm{Sim}_Q - \mathrm{Data}_Q)/\sigma_Q$
$(\mathrm{Sim}_U - \mathrm{Data}_U)/\sigma_U$
$(\mathrm{Sim}_V - \mathrm{Data}_V)/\sigma_V$
Distance from the shower axis [m]

Event # 3



Normalized current
height (km)
$I_{v\times B}$
$I_{v\times[v\times B]}$
Normalized I
data
simulation
Q/I
U/I
V/I
$(Sim_I - Data_I)/\sigma_I$
$(Sim_Q - Data_Q)/\sigma_Q$
$(Sim_U - Data_U)/\sigma_U$
$(Sim_V - Data_V)/\sigma_V$
Distance from the shower axis [m]

Results for events #1, 2, 3

Event - ID	UTC Time	θ (°)	ϕ (°)	h_1 (km)	E_1 (kV/m)	α_1 (°)	h_2 (km)	E_2 (kV/m)	α_2 (°)	h_3 (km)	E_3 (kV/m)	α_3 (°)
1	14/12/2011, 21:02:27	39.4	144.8	7.6	15	-103	3.3	107	119	1.6	42	-109
2	14/12/2011, 21:10:01	14.1	134.0	9.2	42	-174	–	–	–	1.9	86	9
3	14/12/2011, 21:14:34	24.4	333.0	7.9	23	-107	5.0	89	-59	2.3	17	-46
4	26/04/2012, 15:22:33	22.2	129.0	10.1	62	[illegible]	[illegible]	[illegible]	[illegible]	3.0	34	-102

alpha = angle with vxB

Tomography: $\mathbf{E} = \mathbf{E}_{\perp i} + E_{i\|}\mathbf{v}_i = \mathbf{E}_{\perp j} + E_{j\|}\mathbf{v}_j$

Consistency: $\mathbf{E}_{\perp i} \cdot (e_{\mathbf{v}_i \times \mathbf{v}_j}) = \mathbf{E}_{\perp j} \cdot (e_{\mathbf{v}_i \times \mathbf{v}_j})$

Apply to events #1 & 3

Top: $\mathbf{E}_{\perp 1} \cdot (v_1 x v_3)$= 3.0 , $\mathbf{E}_{\perp 3} \cdot (v_1 x v_3)$= 22.6

E (East,North,Up)= (-3.5±5.2, -12.0±8.3 , -19.7±0.4)

~~Middle: $\mathbf{E}_{\perp 1} \cdot (v_1 x v_3)$= -89 , $\mathbf{E}_{\perp 3} \cdot (v_1 x v_3)$= +45~~

~~**E** (East,North,Up)= (-57.±36. , 61.±57 , -3.±3.)~~

Bottom: $\mathbf{E}_{\perp 1} \cdot (v_1 x v_3)$= 4.7 , $\mathbf{E}_{\perp 3} \cdot (v_1 x v_3)$= 5.6

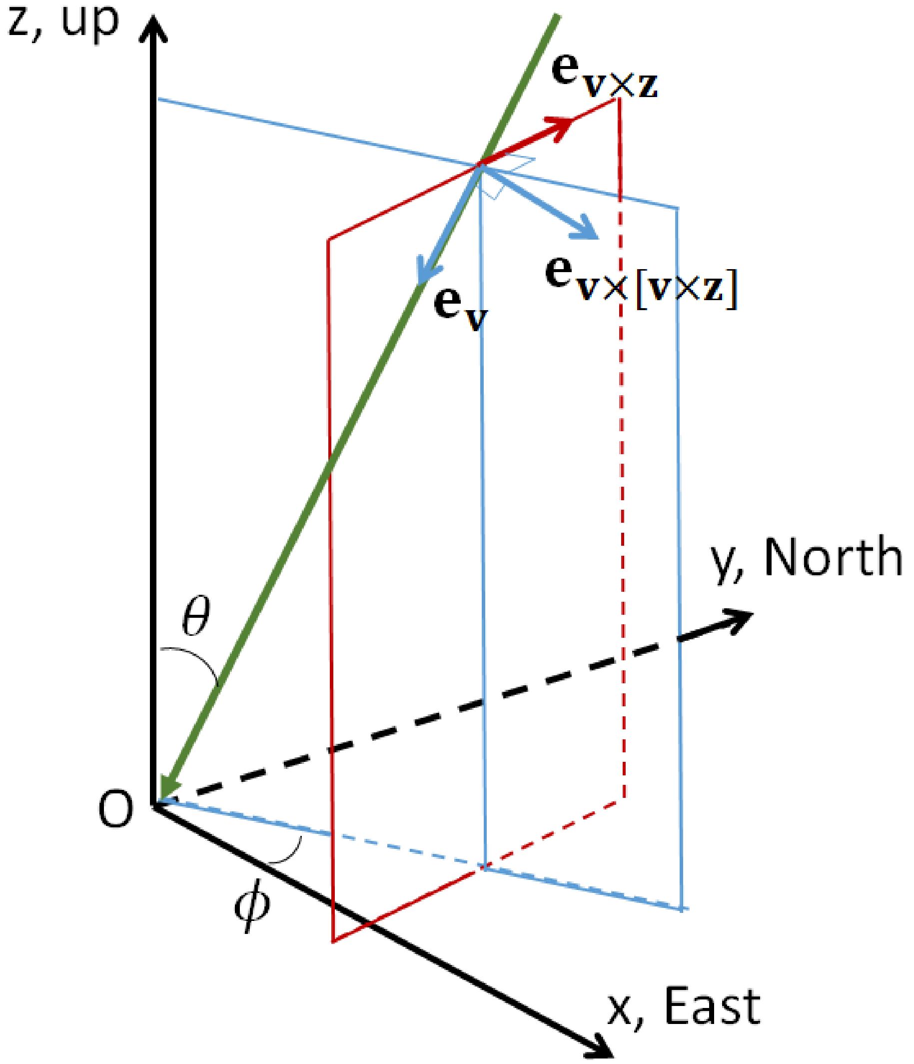
E (East,North,Up)= (4.8±.3 , -6.4±.4 , -56.9±.1)

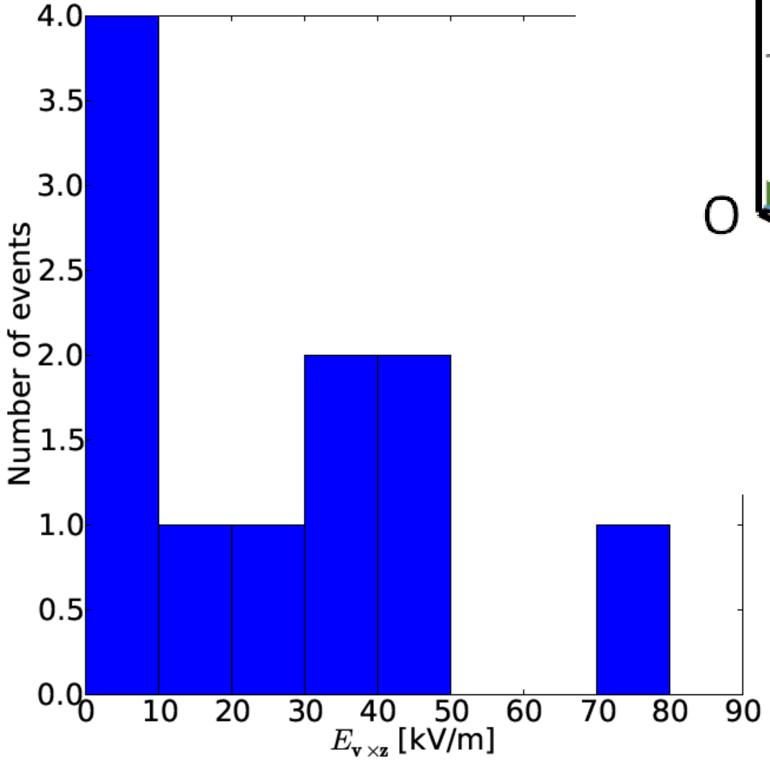
Conclusions

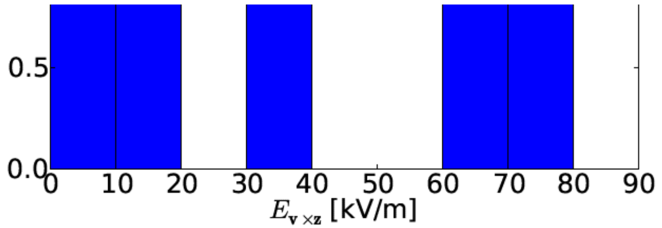
- New –non intrusive – way to determine electric fields in clouds
  → large horizontal components
- Tomography possible to determine vertical components

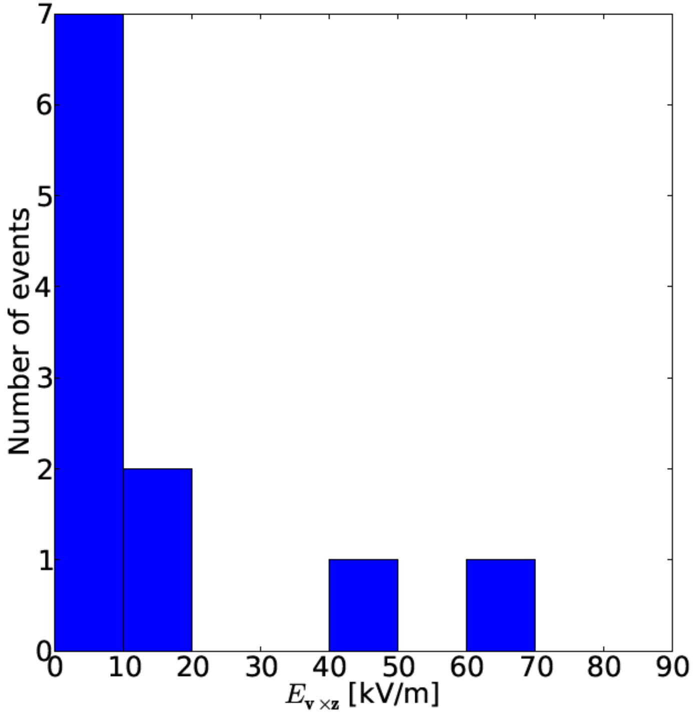
- Even non-thunderclouds have strong electric fields:
  → beware of clouds when analyzing radio emission

Reference:
Thesis Gia Trinh & submitted to Journal of Geophysical Research

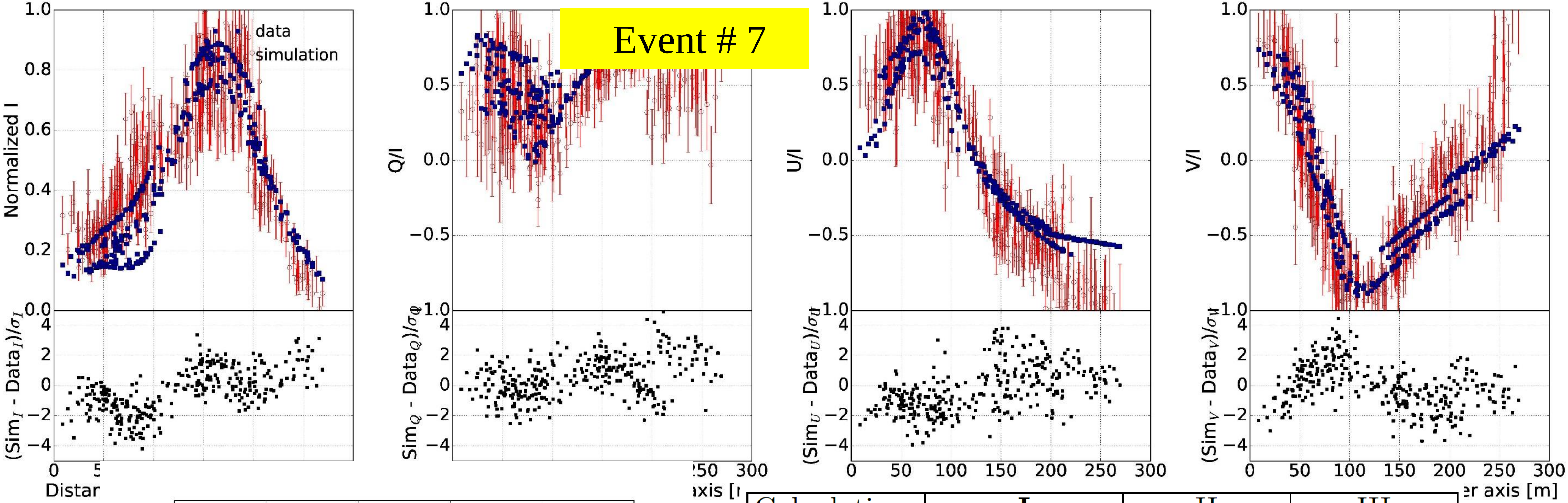

z, up
$e_{v\times z}$
e_v
$e_{v\times[v\times z]}$
y, North
θ
O
ϕ
x, East


Number of events
$E_{v\times z}$ [kV/m]

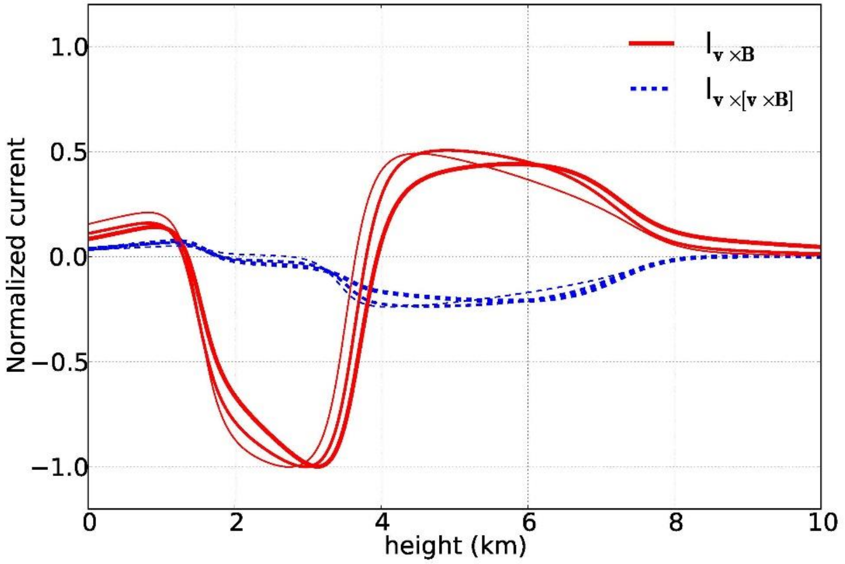

$E_{v\times z}$ [kV/m]


Number of events
$E_{v\times z}$ [kV/m]

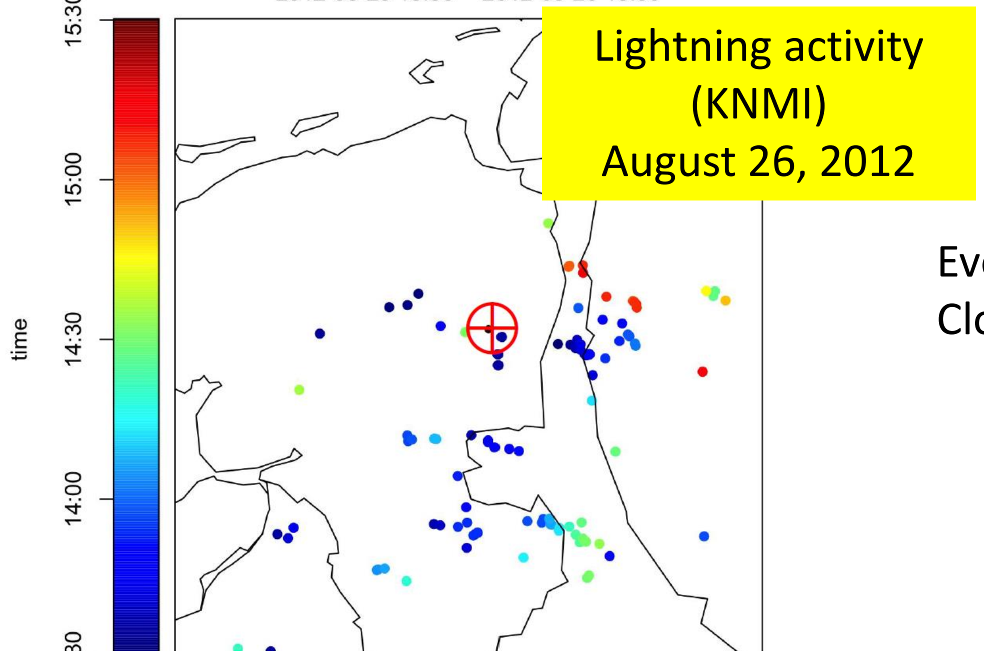
Event # 7



Event



Calculation	**I**			II			III		
Energy (eV)	$\mathbf{5.5 \times 10^{16}}$			3.5×10^{16}			2.0×10^{16}		
Layer	**1**	**2**	**3**	1	2	3	1	2	3
h (km)	**7.3**	**3.6**	**1.7**	7.3	3.5	1.7	7.5	3.4	1.7
E (kV/m)	**13**	**106**	**26**	25	104	20	31	107	20
α (°)	**-35**	**180**	**24**	-31	179	20	-31	177	11
$X_{\max}$ g/cm^2	**550**			650			730		
$X_{\max}$ (km)	**5.4**			4.1			3.2		
χ^2_{3D}	**2.82**			2.29			2.34		
χ^2_C	**1.92**			1.95			2.29		
f_r	**4.9**			5.7			10.0		



Events 6,7,8
Cloud-tops at 9 km